

The nn quasi-free nd breakup cross section: discrepancies to theory and implications on the 1S_0 nn force

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Abstract

Large discrepancies between quasi-free neutron-neutron (nn) cross section data from neutron-deuteron (nd) breakup and theoretical predictions based on standard nucleon-nucleon (NN) and three-nucleon (3N) forces are pointed out. The nn 1S_0 interaction is shown to be dominant in that configuration and has to be increased to bring theory and data into agreement. Using the next-to-leading order (NLO) 1S_0 interaction of chiral perturbation theory (χ PT) we demonstrate that the nn QFS cross section only slightly depends on changes of the nn scattering length but is very sensitive to variations of the effective range parameter. In order to account for the reported discrepancies one must decrease the nn effective range parameter by about $\approx 12\%$ from its value implied by charge symmetry and charge independence of nuclear forces.

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I. INTRODUCTION

The knowledge of the NN interaction is fundamental for interpreting nuclear phenomena. The proton-proton (pp) experiments provide a solid data basis [1, 2], which restricts theoretical assumptions about the strong part of the pp force. In case of the neutron-proton (np) system this is only true to a smaller extent. The partial wave analysis of the np data [2] relies on the assumption that the isospin $t = 1$ piece can be taken over from the pp system and only the $t = 0$ part is free in the adjustment to the data. The lack of a free neutron target forbids neutron-neutron (nn) experiments, therefore the information on the nn interaction can be deduced only in an indirect way. To that aim the best tool seems to be the study of the three-nucleon (3N) system composed from two neutrons and the proton. It is simple enough to allow a rigorous theoretical treatment, e.g. in the framework of Faddeev equations [3]. The neutron-deuteron elastic scattering together with the neutron induced deuteron breakup, supplemented with the triton properties, offer a data basis which can be used to test properties of the nn force. Especially the nd breakup process with its rich set of configurations for free three outgoing nucleons seems to be a powerful tool to test the nuclear Hamiltonian. By comparing theoretical predictions to the nd breakup data in different configurations not only can the present day models of two-nucleon (2N) interactions be tested, but also effects of three-nucleon forces (3NF's) can be studied.

The nn quasi-free scattering (QFS) refers to a situation where the outgoing proton is at rest in the laboratory system. In the nd breakup also np QFS is possible. Here one of the neutrons is at rest while the second neutron together with the proton form a quasi-freely scattered pair.

The reported nn QFS cross sections taken at $E_n^{lab} = 26$ MeV [4] and at $E_n^{lab} = 25$ MeV [5] overestimate the nd theory by $\approx 18\%$. Surprisingly, when instead of the nn pair the np pair is quasi-freely scattered, the theory follows nicely the np QFS cross section data taken in the $E_n^{lab} = 26$ MeV nd breakup measurement [4]. That good description of the np QFS cross section contrasts with the drastic discrepancy between the theory and the nn QFS cross section data taken in the same experiment [4].

We do not expect surprises in case of the pp QFS data [6–8], since the information of the rich set of pp data has been incorporated into the pp forces. In fact a recent analysis [9] including the Coulomb force to pp QFS data lead to a nice agreement, while in previous analysis [6–8] the Coulomb force was not yet included. Additional theoretical efforts to include all effects of the Coulomb force beyond the ones in [9] are underway.

In section II we exemplify the stability of the QFS cross sections against changes of modern

nuclear forces. We also demonstrate that below ≈ 30 MeV the 1S_0 and 3S_1 - 3D_1 NN force components dominate the QFS cross sections. In section III we analyse the np as well as the nn QFS data from [4] in terms of rigorous solutions of the 3N Faddeev equation and discuss necessary changes in the 1S_0 nn force component to remove the discrepancies in the nn QFS cross section. Thereby a detailed study is performed using the next-to-leading order (NLO) chiral NN force, composed of contact interactions and the one-pion exchange potential. It reveals that the effective range parameter is decisive to reconcile theory and data. The outcome is discussed in section IV and further experimental insights on the nn force are proposed. Finally we summarize in section V.

II. STABILITY AND SENSITIVITY STUDIES

It is known that nd scattering theory provides QFS cross sections which are highly independent from the realistic NN potential used in the calculations and that they practically do not change when any of the present day 3NF's is included [3, 10, 11]. We exemplify it in Fig. 1 for the nn and np QFS geometries of ref. [4]. There results of 3N Faddeev calculations [3] based on different high precision NN forces (CD Bonn [13], Nijm I and Nijm II [14]) alone or combined with the TM99 3NF [15, 16] are shown.

The sensitivity study performed in [10] revealed that at energies below ≈ 30 MeV the 1S_0 and 3S_1 - 3D_1 NN force components provide the most dominant contribution to the QFS cross sections with much less contributions of higher partial waves. Specifically, in the np QFS geometries the 3S_1 - 3D_1 is the dominant force component while for nn QFS it is the 1S_0 force which contributes decisively. Again we exemplify it for nn and np QFS geometries of ref. [4] in Fig. 2.

Such a dominance for the QFS peak is understandable since the QFS cross sections are practically insensitive to the action of the presently available 3NF. Then at low energy the largest contribution should be provided by the S-wave components of the NN potential. In case of free np and nn scattering these are the $^1S_0(\text{np}) + ^3S_1 - ^3D_1$ and $^1S_0(\text{nn})$ contributions, respectively. In the simple minded spirit that under QFS condition one of the three nucleons (at rest in the lab system) is just a spectator such a dominance of a two-nucleon encounter is to be expected. In reality, however, the projectile nucleon also interacts with that "spectator" particle and the three nucleons at low energies undergo higher order rescatterings [3, 12]. Thus the scattering to the final nn (np) QFS configuration also receives contributions from the np $^3S_1 - ^3D_1$ (nn 1S_0) interaction. Despite of all that the numerical results clearly reveal that for the np QFS configuration the $^3S_1 - ^3D_1$ force is the most dominant contribution and for the nn QFS it is the 1S_0 force (for

free nn scattering there is no ${}^3S_1 - {}^3D_1$ interaction possible). This implies that the nn QFS is a powerful tool to study the 1S_0 nn force component.

That extreme sensitivity of the nn QFS cross section to the 1S_0 nn force component is demonstrated in Fig. 3 for the QFS geometries of ref. [4]. To that aim we multiplied the 1S_0 nn matrix element of the CD Bonn potential by a factor λ . The result is, that the nn QFS cross section undergoes significant variations while the np QFS cross section is practically unchanged. The displayed λ -parameters include also the value $\lambda = 1.08$ which is necessary to get agreement with the nn QFS data of ref.[4].

While both, 1S_0 and ${}^3S_1 - {}^3D_1$, np forces are well determined by np scattering data (with the restrictions mentioned above) and by the deuteron properties, the 1S_0 nn force is determined up to now only indirectly due to lack of free nn data. The disagreement between data and theory in the nn QFS peak points to the possibility of a flaw in the nn 1S_0 force. It was shown in [10] that in order to remove the $\approx 18\%$ discrepancy found in [4] for the nn QFS cross section required an increased strength of the 1S_0 nn interaction which when given in terms of a factor λ amounts to $\lambda \approx 1.08$. In Fig. 4 we show the effect of the λ -modification for the nn scattering length a_{nn} and for the effective range parameter r_{eff} , and in Fig. 5 for the binding energy of two neutrons in the 1S_0 state. It is seen that taking $\lambda = 1.08$ leads to a nearly bound state of two neutrons.

III. IMPLICATIONS ON THE 1S_0 NN EFFECTIVE RANGE PARAMETER

Since the multiplication of the 1S_0 potential matrix element by a factor λ induces changes in the effective range as well as in the scattering length the question arises, which from both effects is more important for the nn QFS cross section variations? To answer that question we performed 3N Faddeev calculations based on the next-to-leading (NLO) order χ PT potential [17, 18] including all np and nn forces up to the total angular momentum $j_{max} = 3$ in the two-nucleon subsystem. The 1S_0 component of that interaction is composed of the one-pion exchange potential and contact interactions parametrized by two parameters \tilde{C}_{1S_0} and C_{1S_0}

$$V({}^1S_0) = \tilde{C}_{1S_0} + C_{1S_0}(p^2 + p'^2) . \quad (1)$$

Standard values are $\tilde{C}_{1S_0} = -0.1557374 * 10000 \text{ GeV}^{-2}$ and $C_{1S_0} = 1.5075220 * 10000 \text{ GeV}^{-4}$ for cut-off combinations $\{\Lambda, \tilde{\Lambda}\} = \{450 \text{ MeV}, 500 \text{ MeV}\}$ [18].

Multiplying \tilde{C}_{1S_0} by a factor $C_2({}^1S_0)$ and C_{1S_0} by a factor $C_1({}^1S_0)$ one can induce changes of the nn 1S_0 interaction. Requiring either the value of the scattering length a_{nn} or the value of the

effective range parameter r_{eff} to be constant correlates the $C_1(^1S_0)$ and $C_2(^1S_0)$ factors.

Changing $C_1(^1S_0)$ and $C_2(^1S_0)$ in such a way that the scattering length is kept constant and equal $a_{nn} = -17.6$ fm leads to changes of the effective range r_{eff} shown in Fig. 6. The resulting changes of the nn and np QFS cross sections for geometries of ref. [4] are shown in Fig. 7 for five sets of $C_1(^1S_0)$ and $C_2(^1S_0)$ factors with different nn 1S_0 effective range parameters ranging from $r_{eff} = 2.03$ fm to $r_{eff} = 3.07$ fm; one of them corresponding to the value required by the data.

Similarly, changing $C_1(^1S_0)$ and $C_2(^1S_0)$ while keeping the effective range constant to $r_{eff} = 2.75$ fm, leads to changes of the nn 1S_0 scattering length a_{nn} shown in Fig. 8. The resulting changes of the nn and np QFS cross sections are presented in Fig. 9 for four values of the nn 1S_0 scattering length ranging from $a_{nn} = -10.9$ fm to $a_{nn} = -75.9$ fm. It is clearly seen that the nn QFS cross sections depend only slightly on a change of the scattering length. The variations of the QFS cross section maximum stays below $\approx \pm 4\%$. On the other side much stronger variations of the nn QFS cross sections result from changes of the effective range (see Fig. 7).

Thus we can conclude that the λ -enhancement mechanism for the 1S_0 nn force studied in [10] acts mainly through the change of the effective range parameter. Thus in order to remove the discrepancies found in [4] and [5] for the nn QFS cross section a change of the nn 1S_0 effective range parameter is required. Its value taken under the assumption of charge symmetry and charge independence of nuclear forces is $r_{eff} = 2.75$ fm and it has to be changed to $r_{eff} \approx 2.41$ fm. That implies a large charge symmetry and charge independence breaking effect of about $\approx 12\%$ for that parameter.

We would like to add that the discussed changes of r_{eff} did not affect the elastic nd cross section nor vector or tensor analysing powers to a measurable extent. Only more complicated spin observables in elastic nd scattering are affected but the present day experimental errors are much larger than those changes.

IV. DISCUSSION AND FURTHER EXPERIMENTAL INFORMATION

Is such a large isospin breaking effect at all possible in view of the present understanding of nuclear forces?

First of all it seems improbable that only the effective range would reveal large isospin breaking and the scattering length will be left unaffected. In χ PT the leading isospin breaking contribution is provided by isospin breaking contact interaction without derivatives [19]. It turns out that the effective range parameter is quite insensitive to that isospin breaking contact force and typical

isospin breaking effects for r_{eff} are small and under $\approx 1\%$ [19].

The reported discrepancies for nn QFS require however a much larger effect for r_{eff} of the order $\approx 12\%$. Only when the contact terms in next orders would be unnaturally large one could expect larger isospin breaking effects for r_{eff} . Assuming naturalness it seems rather improbable.

Since it seems unlikely that isospin breaking effects will show up, if at all, in the effective range parameter alone without affecting simultaneously the nn scattering length, the question of a possible existence of a bound state of two neutrons reappears.

Present day NN interactions allow only one bound state of two nucleons, namely the deuteron, where the neutron and the proton are interacting in a state with angular momenta $l = 0$ or 2 , total spin $s = 1$, and total angular momentum $j = 1$. When the neutron and proton are interacting with the 1S_0 force no bound state exists and only a virtual resonant state occurs as documented by the negative scattering length $a_{np} = -21.73$ fm. Also the data for the proton-proton system exclude a 1S_0 pp bound state; however in this case the nuclear force is overpowered by the strong pp Coulomb repulsion. Assuming charge-independence and charge-symmetry of strong interactions also the two neutrons should not bind in the 1S_0 state.

It also seems that modern nuclear forces do not allow for the 3n and 4n systems to be bound [20]. However, in view of the strong discrepancies between theory and data found in the nd breakup measurements for the nn QFS geometry, which cannot be explained by present day nuclear forces, it appears reasonable to check experimentally the possibility of two neutrons being bound.

There are reactions which provide conditions advantageous for a hypothetical di-neutron bound state. Such conditions can be found e.g. when two neutrons are moving with equal momenta and with relative energy close to zero. That occurs in the so called final-state-interaction (FSI) geometry of the nd breakup. Incomplete nd breakup measurements have been performed in the past to study properties of the 1S_0 nn force [21]. Even a dedicated experiment was performed in order to look for a hypothetical 1S_0 nn bound state [22] in which the spectrum of the proton going in forward direction has been measured with the aim of a precise determination of its high energy region. The negative result of [22] showed that the nd reaction is not suitable for such a study.

It seems that much more appropriate would be reactions in which from the beginning two neutrons occupy a configuration advantageous for their binding.

It is known [23, 24] that ^3He is predominantly a spatially symmetric S state with its two protons mainly in opposite spin states. This component amounts for $\approx 90\%$ of the ^3He wave function. Similarly, the two neutrons in ^3H are restricted to be in a spin-singlet state. That makes the triton target a very suitable tool to look for a nn bound state in γ induced breakup of ^3H . The

idea is to measure the spectra of the outgoing protons in such a reaction. The two-neutron bound state, if existent, should reveal itself as a peak above the highest available proton energy from the 3-body decay of ${}^3\text{H}$. We show in Figs. 10 to 11 the outgoing proton spectra from the $\gamma({}^3\text{H}, p)nn$ reaction for a number of γ energies and angles of the outgoing protons. The big advantage of that reaction is that γ interacts predominantly with the proton.

Also other reactions, such as e.g. ${}^3\text{H}(n, d)nn$ and ${}^3\text{H}(d, {}^3\text{He})nn$, provide conditions advantageous for two neutrons to bind. They are complimentary and independent from the ${}^3\text{H}(\gamma, p)nn$ reaction and the data from all three processes should provide an answer to the question whether two neutrons can form a bound state. The reaction ${}^3\text{H}(d, {}^3\text{He})nn$ cannot presently be treated in a theoretically rigorous manner, however with the rapid increase in computer power such a treatment based on Faddeev-Yakubovsky equations can be expected in the near future.

V. SUMMARY

The strong discrepancy in the nn QFS nd break up configuration found in [4, 5] is reconsidered. It is documented again that at low energies (below ≈ 30 MeV) the nn (np) QFS cross section depends dominantly only on the 1S_0 (${}^3S_1 - {}^3D_1$) NN force component and higher partial wave contributions are quite small. Furthermore the theoretical results are quite stable under exchange of the standard nuclear forces. Also the present day available 3N forces have negligible effect on the QFS configurations. Since no direct measurement of the nn force is available there is the possibility that the properties of the nn force are still unsettled. Thus simply multiplying the nn 1S_0 force matrix element by a factor $\lambda = 1.08$ one can perfectly well reconcile theory and data. In addition we performed a more detailed study using the NLO chiral potential, which is composed of the one-pion exchange and contact interactions depending on two parameters. That dependence allowed us to study separately variations in the scattering length a_{nn} leaving the effective range parameter r_{eff} constant and vice versa. Thereby it turned out that the nn QFS peak height is very sensitive to r_{eff} and hardly sensitive to a_{nn} . The outcome for an agreement with the data is the requirement that r_{eff} decreases from the value $r_{eff} = 2.75$ fm to a significantly smaller one, $r_{eff} = 2.41$ fm. That strongly breaks charge symmetry and charge independence and is not supported by present day chiral potential theory.

So, what might be a solution to remove the discrepancy?

If the data are taken for granted there remains the possibility that a di-neutron exists. We propose additional experimental investigations, like the ${}^3\text{H}(\gamma, p)nn$ process and evaluated the proton

spectra at various emission angles emphasizing its high energy region.

The direct inclusion of Δ -degrees of freedom into χ PT allows for a rich set of additional NN and 3N force diagrams which are presently under investigation [27]. This might reconcile theory and data also for the space-star discrepancy [3] in the nd breakup process.

Right now the situation is unsettled.

Acknowledgments

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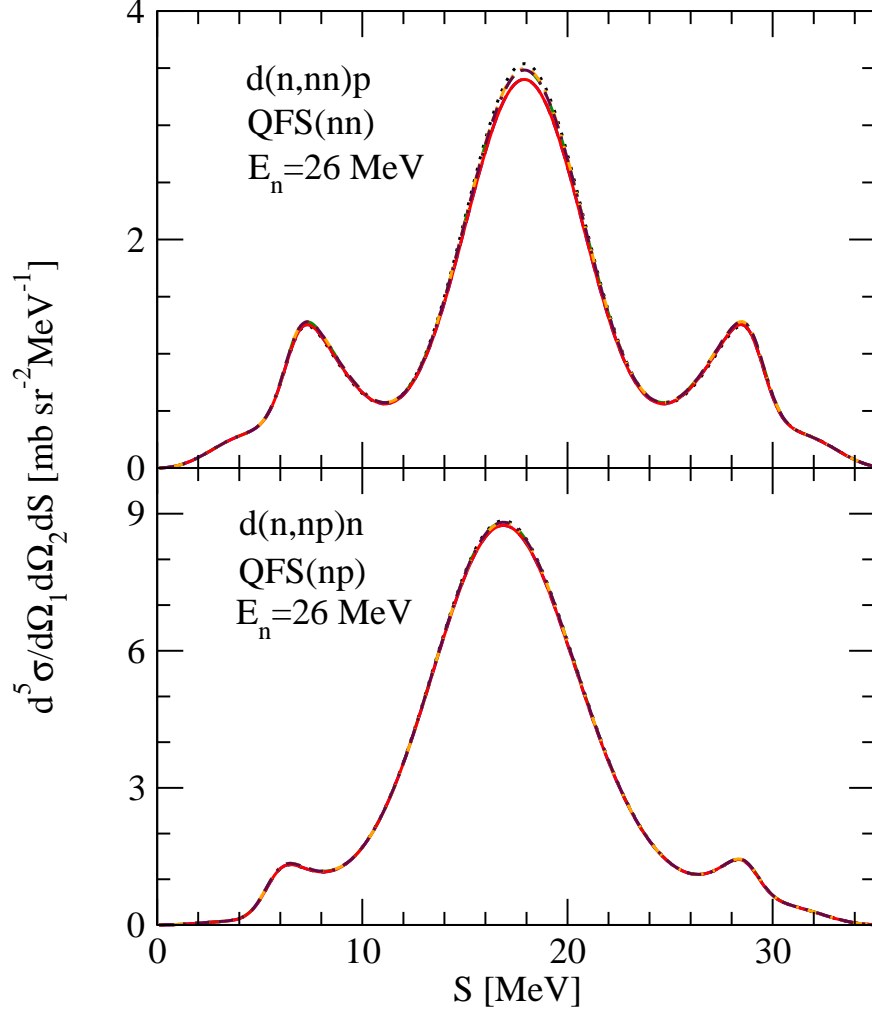


FIG. 1: (color online) The cross section $d^5\sigma/d\Omega_1 d\Omega_2 dS$ for the $E_n^{lab} = 26$ MeV nd breakup reaction $d(n, nn)p$ (upper panel) and $d(n, np)n$ (lower panel) as a function of the S-curve length for two complete configurations of Ref. [4]. QFS nn refers to the angles of the two neutrons: $\theta_1 = \theta_2 = 42^\circ$ and QFS np refers to the angle $\theta_1 = 39^\circ$ of the detected neutron and $\theta_2 = 42^\circ$ for the proton. In both cases $\phi_{12} = 180^\circ$. The (practically overlapping) lines correspond to different underlying dynamics: CD Bonn [13] - dashed (blue), Nijm I - dotted (black), Nijm II [14] - dashed-dotted (green), CD Bonn+TM99 - solid (red), Nijm I +TM99 [15, 16] - dashed-double-dotted (orange), Nijm II + TM99 - double-dashed-dotted (maroon). All partial waves with 2N total angular momenta up to $j_{max} = 5$ have been included.

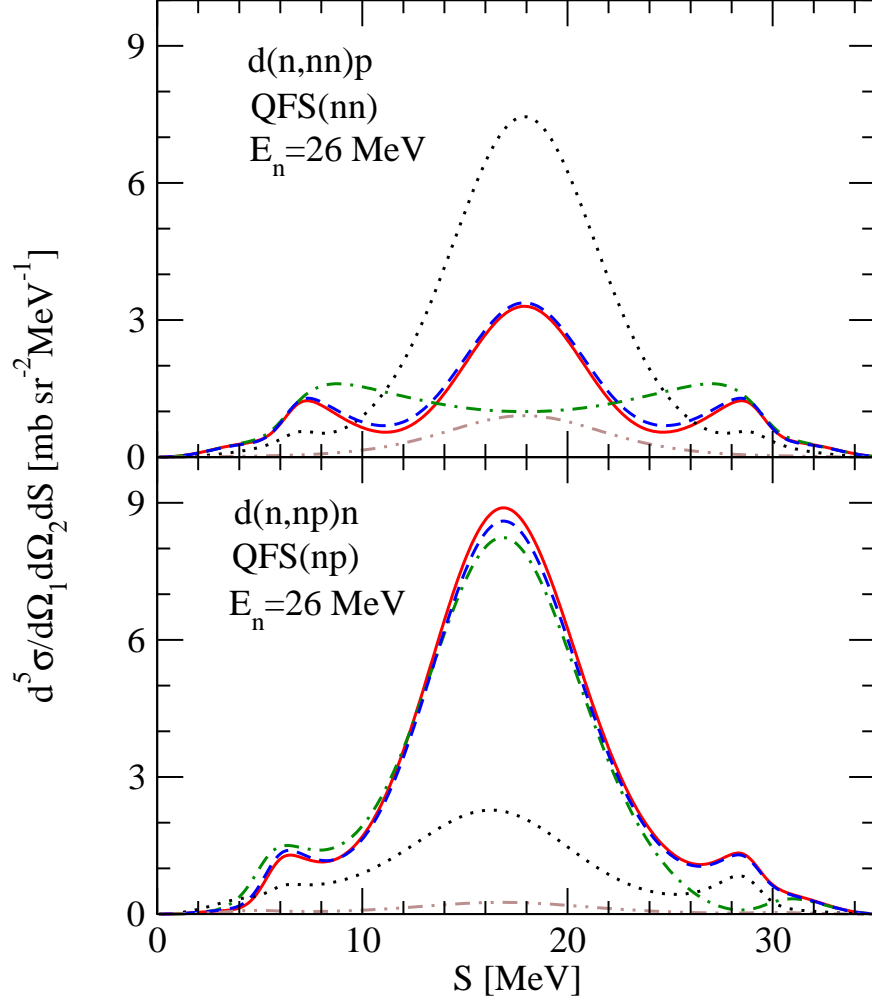


FIG. 2: (color online) The cross section $d^5\sigma/d\Omega_1 d\Omega_2 dS$ for the $E_n^{lab} = 26$ MeV nd breakup reaction $d(n, nn)p$ (upper panel) and $d(n, np)n$ (lower panel) as a function of the S-curve length for two complete configurations of Ref. [4] specified in Fig. 1. The different lines show contributions from different NN force components. The solid (red) line is the full result based on the CD Bonn potential [13] and all partial waves with $2N$ total angular momenta up to $j_{max} = 5$ included. The dotted (black), dashed-dotted (green), and dashed (blue) lines result when only contributions from 1S_0 , $^3S_1 - ^3D_1$, and $^1S_0 + ^3S_1 - ^3D_1$ are kept calculating the cross sections. The dashed-double-dotted (brown) line presents the contribution of all partial waves with the exception of 1S_0 and $^3S_1 - ^3D_1$.

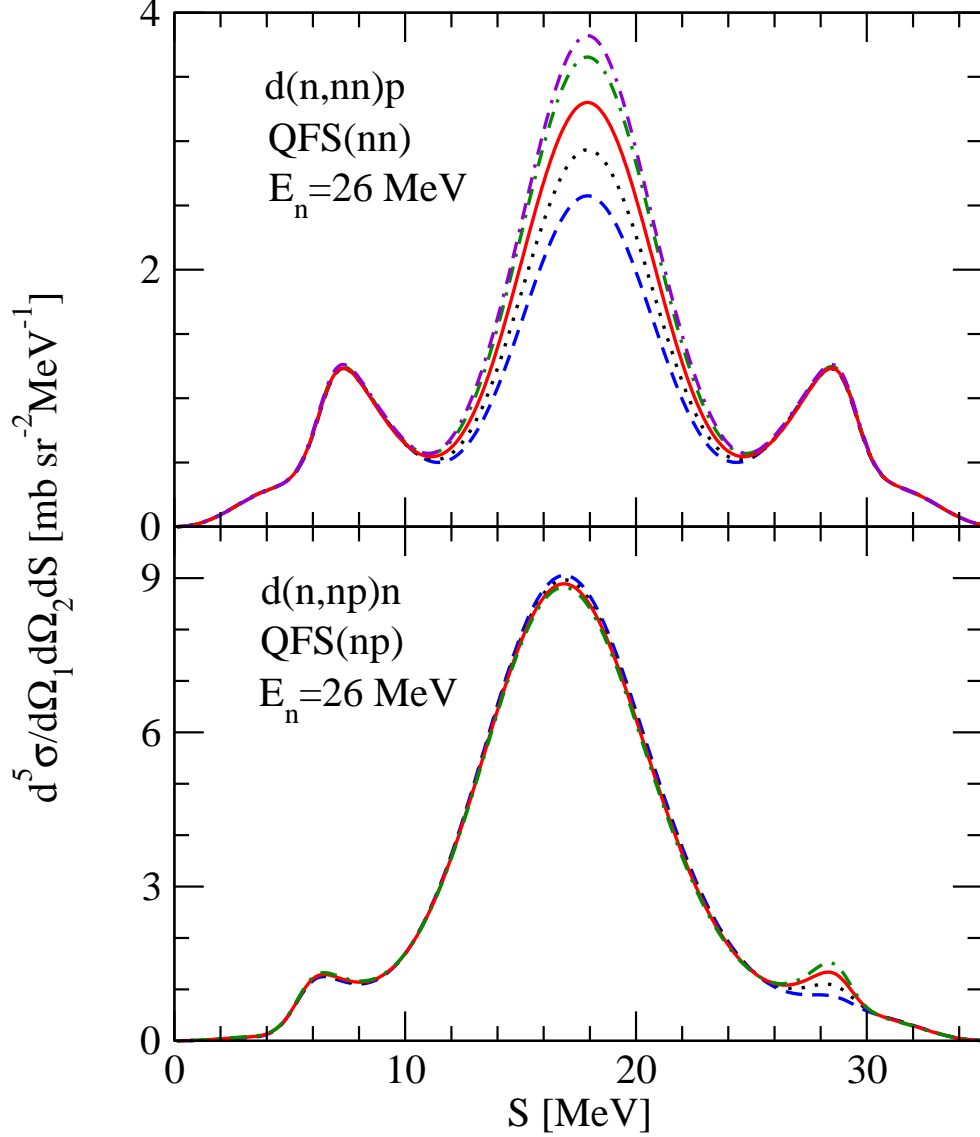


FIG. 3: (color online) The cross section $d^5\sigma/d\Omega_1 d\Omega_2 dS$ for the $E_n^{lab} = 26 \text{ MeV}$ nd breakup reaction $d(n, nn)p$ (upper panel) and $d(n, np)n$ (lower panel) as a function of the S-curve length for two complete configurations of Ref. [4] specified in Fig. 1. The lines show sensitivity of the QFS cross sections to the changes of the nn 1S_0 force component. Those changes were induced by multiplying the 1S_0 nn matrix element of the CD Bonn potential by a factor λ . The solid (red) line is the full result based on the original CD Bonn potential [13] ($a_{nn} = -18.8 \text{ fm}$, $r_{eff} = 2.79 \text{ fm}$) and all partial waves with $2N$ total angular momenta up to $j_{max} = 5$ included. The dashed (blue), dotted (black), and dashed-dotted (green) lines correspond to $\lambda = 0.9$ ($a_{nn} = -8.3 \text{ fm}$, $r_{eff} = 3.12 \text{ fm}$), 0.95 ($a_{nn} = -11.7 \text{ fm}$, $r_{eff} = 2.96 \text{ fm}$), and 1.05 ($a_{nn} = -42.0 \text{ fm}$, $r_{eff} = 2.66 \text{ fm}$), respectively. The double-dashed-dotted (violet) line shows cross sections obtained with $\lambda = 1.08$ ($a_{nn} = -134.7 \text{ fm}$, $r_{eff} = 2.61 \text{ fm}$), which factor is required to get agreement with nn QFS data of ref. [4].

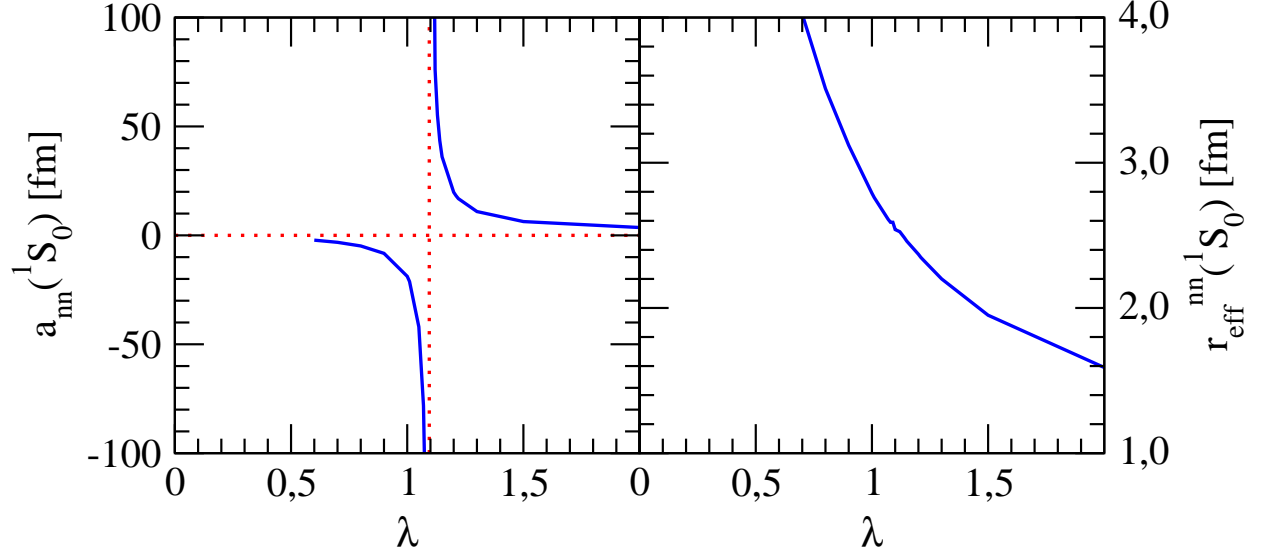


FIG. 4: (color online) The changes of the nn scattering length a_{nn} and the effective range parameter r_{eff} with factor λ by which the 1S_0 nn matrix element of the CD Bonn potential is multiplied: $V_{nn}(^1S_0) = \lambda * V_{CD\ Bonn}(^1S_0)$.

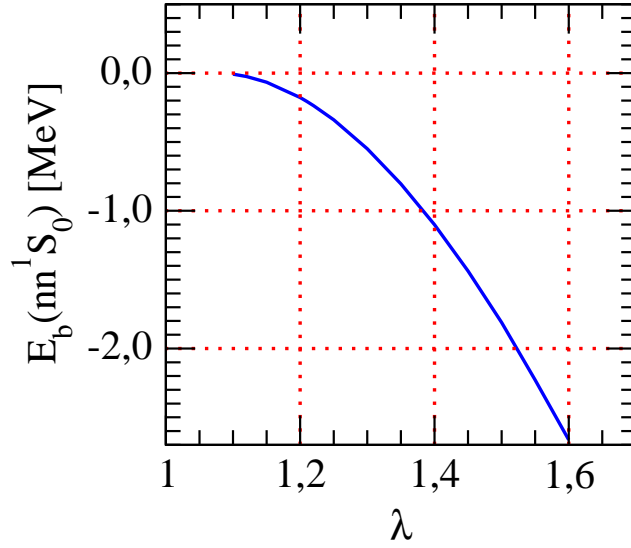


FIG. 5: (color online) The range of λ values by which the 1S_0 nn matrix element of the CD Bonn potential is multiplied ($V_{nn}(^1S_0) = \lambda * V_{CD\ Bonn}(^1S_0)$), for which the two neutrons form a bound state with the binding energy E_b .

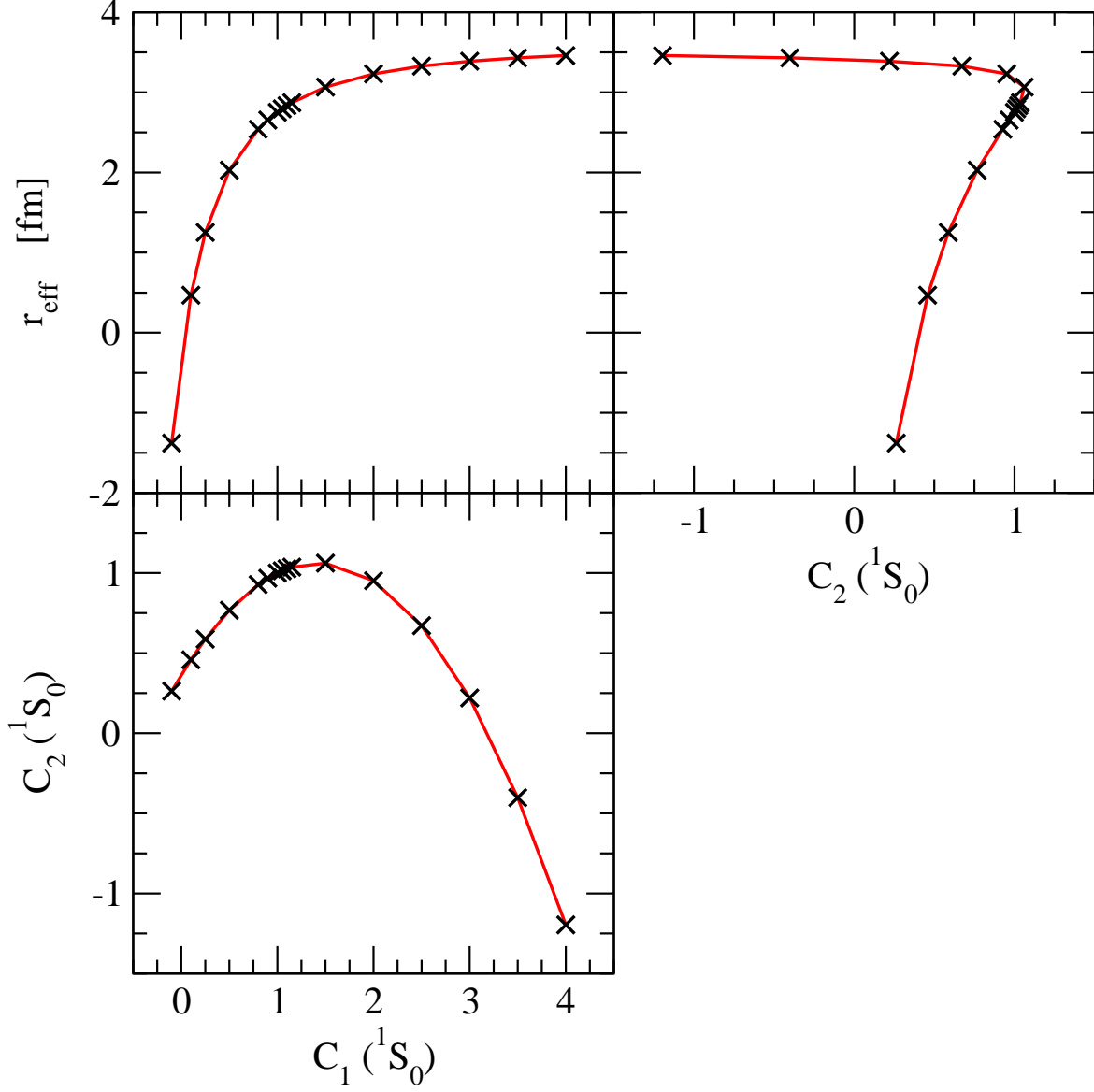


FIG. 6: (color online) Changes of the effective range parameter r_{eff} in the 1S_0 partial wave caused by a correlated change of the factors $C_1(^1S_0)$ and $C_2(^1S_0)$ as shown in bottom part of this figure. This correlation between the factors $C_1(^1S_0)$ and $C_2(^1S_0)$ corresponds to a constant value of the scattering length $a_{nn} = -17.6$ fm.

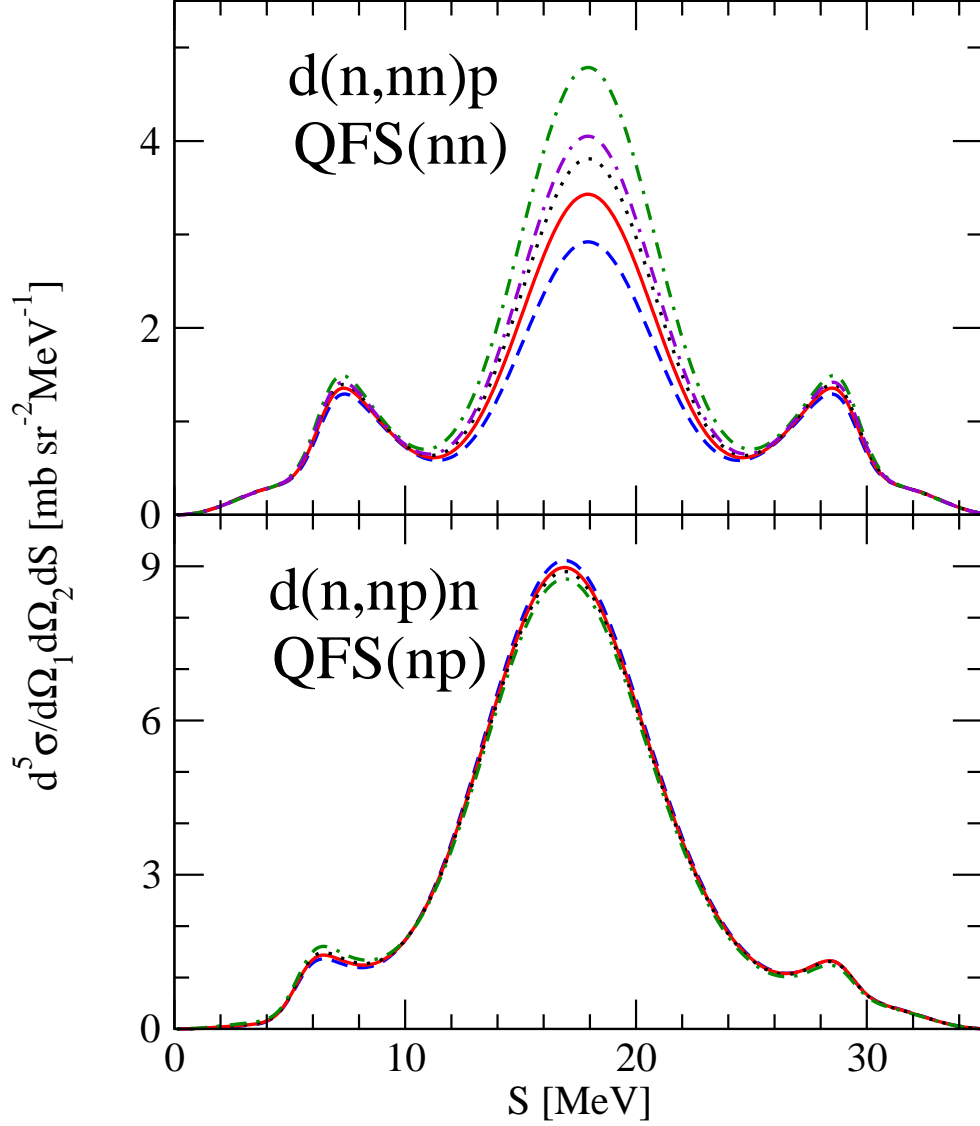


FIG. 7: (color online) Changes of QFS cross sections for configurations specified in Fig. 1 caused by correlated change of factors $C_1(^1S_0)$ and $C_2(^1S_0)$ shown in Fig. 6. All lines show results of Faddeev calculations based on LO χ PT potential and all partial waves with $2N$ total angular momenta up to $j_{max} = 3$ included. They differ in the nn 1S_0 force which was obtained keeping constant scattering length $a_{nn} = -17.6$ fm and changing constants $C_1(^1S_0)$ and $C_2(^1S_0)$ to get different effective ranges which are: solid (red line) - $C_1(^1S_0) = 1.0$, $C_2(^1S_0) = 1.0$, $r_{eff} = 2.75$ fm, dashed (blue line) - $C_1(^1S_0) = 1.5$, $C_2(^1S_0) = 1.0615$, $r_{eff} = 3.07$ fm, dotted (black line) - $C_1(^1S_0) = 0.8$, $C_2(^1S_0) = 0.9275$, $r_{eff} = 2.54$ fm, dashed-dotted (green line) - $C_1(^1S_0) = 0.5$, $C_2(^1S_0) = 0.7675$, $r_{eff} = 2.03$ fm. The double-dashed-dotted (violet) line shows cross sections obtained with $C_1(^1S_0) = 0.7064$, $C_2(^1S_0) = 0.8842$, $r_{eff} = 2.41$ fm, which are required to get agreement with nn QFS data of ref.[4].

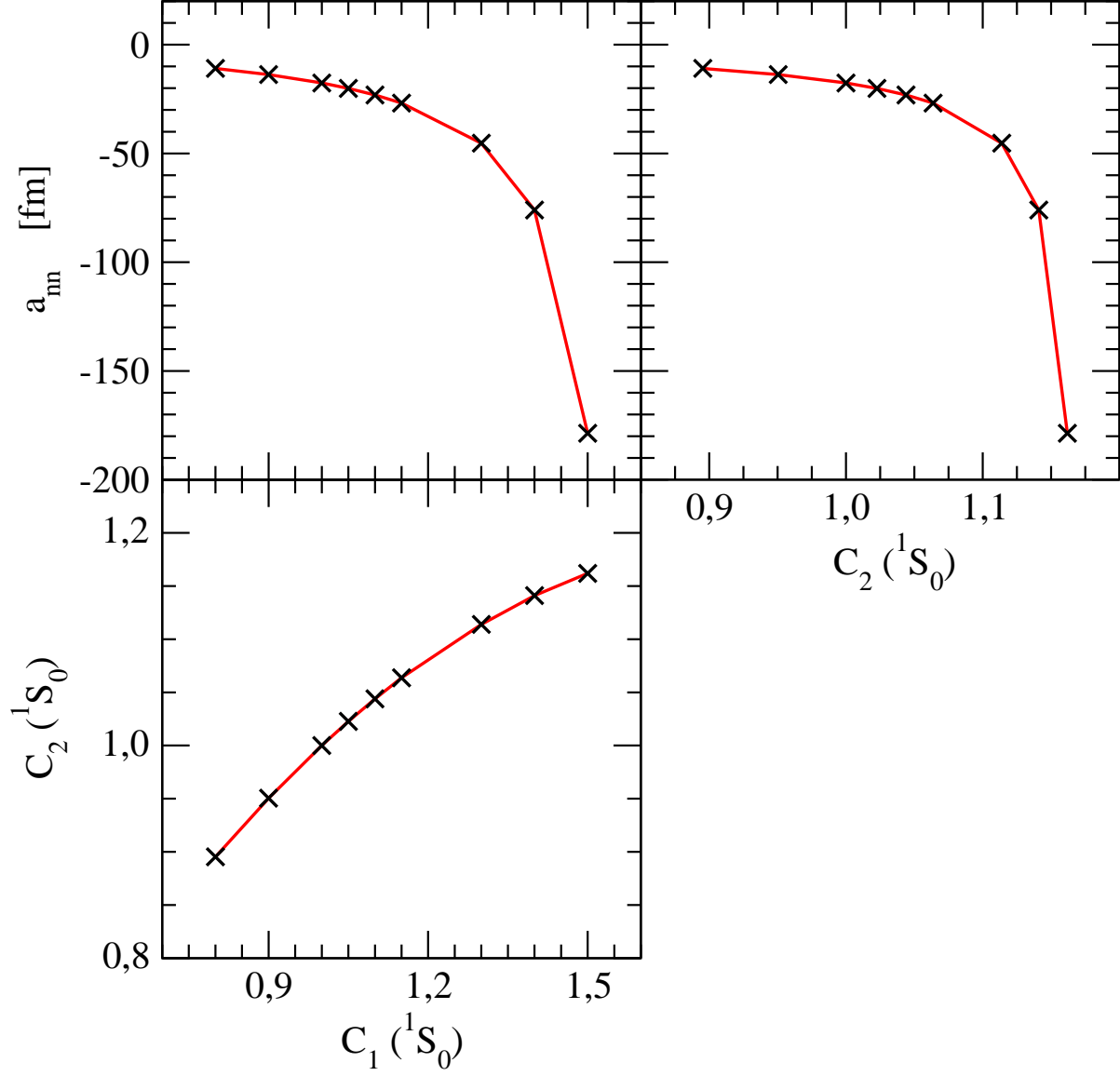


FIG. 8: (color online) Changes of the nn scattering length a_{nn} in the 1S_0 partial wave caused by a correlated change of the factors $C_1(^1S_0)$ and $C_2(^1S_0)$ as shown in the bottom part of this figure. This correlation between the factors $C_1(^1S_0)$ and $C_2(^1S_0)$ corresponds to a constant value of the effective range parameter $r_{eff} = 2.75$ fm.

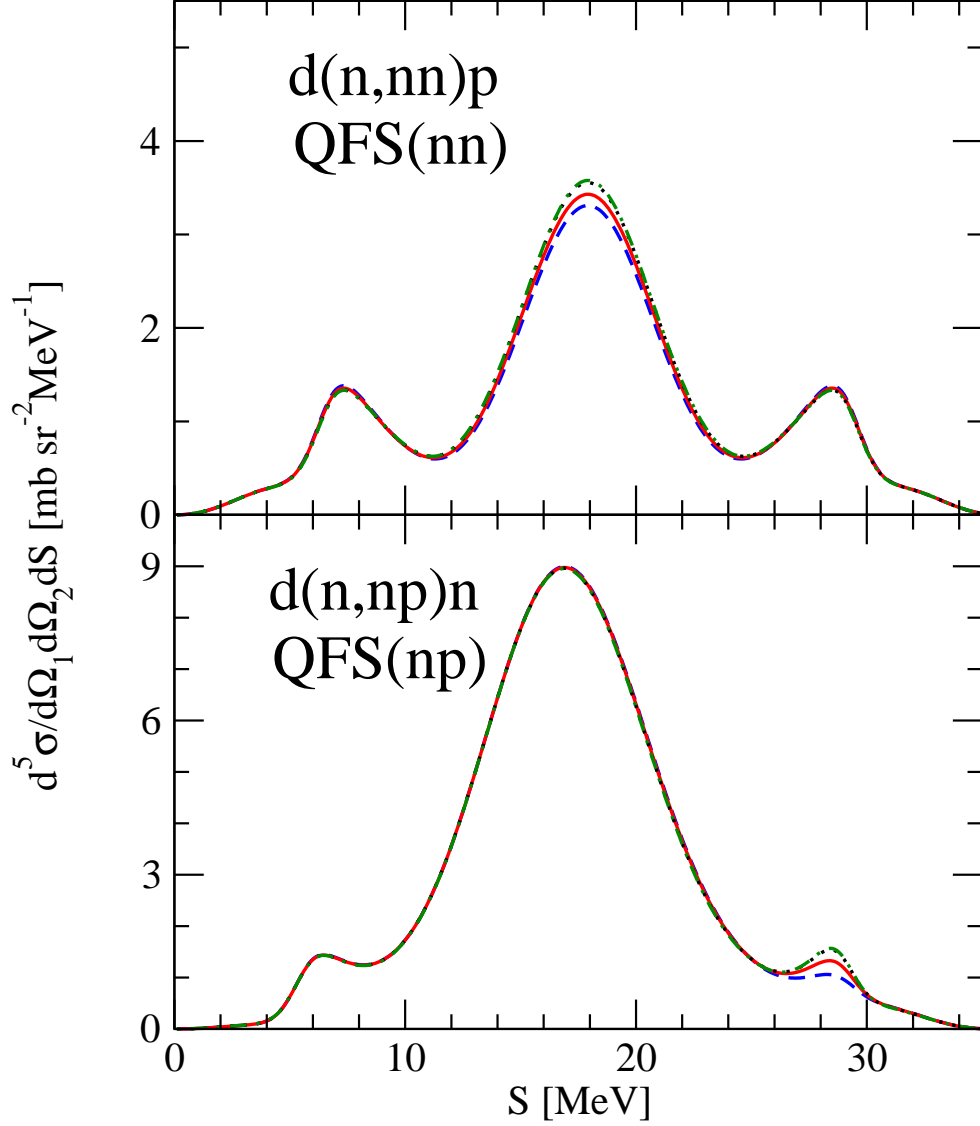


FIG. 9: (color online) Changes of QFS cross sections for configurations specified in Fig. 1 caused by a correlated change of the factors $C_1(^1S_0)$ and $C_2(^1S_0)$ shown in Fig. 8. All lines show results of Faddeev calculations based on the NLO χ PT potential and all partial waves with $2N$ total angular momenta up to $j_{max} = 3$ included. They differ in the nn 1S_0 force which was obtained keeping the effective range parameter $r_{eff} = 2.75$ fm constant and changing the constants $C_1(^1S_0)$ and $C_2(^1S_0)$ to get different scattering lengths which are: solid (red line) - $C_1(^1S_0) = 1.0$, $C_2(^1S_0) = 1.0$, $a_{nn} = -17.6$ fm, dashed (blue line) - $C_1(^1S_0) = 0.8$, $C_2(^1S_0) = 0.8953$, $a_{nn} = -10.9$ fm, dotted (black line) - $C_1(^1S_0) = 1.3$, $C_2(^1S_0) = 1.1139$, $a_{nn} = -45.3$ fm, dashed-dotted (green line) - $C_1(^1S_0) = 1.4$, $C_2(^1S_0) = 1.1410$, $a_{nn} = -76.0$ fm.

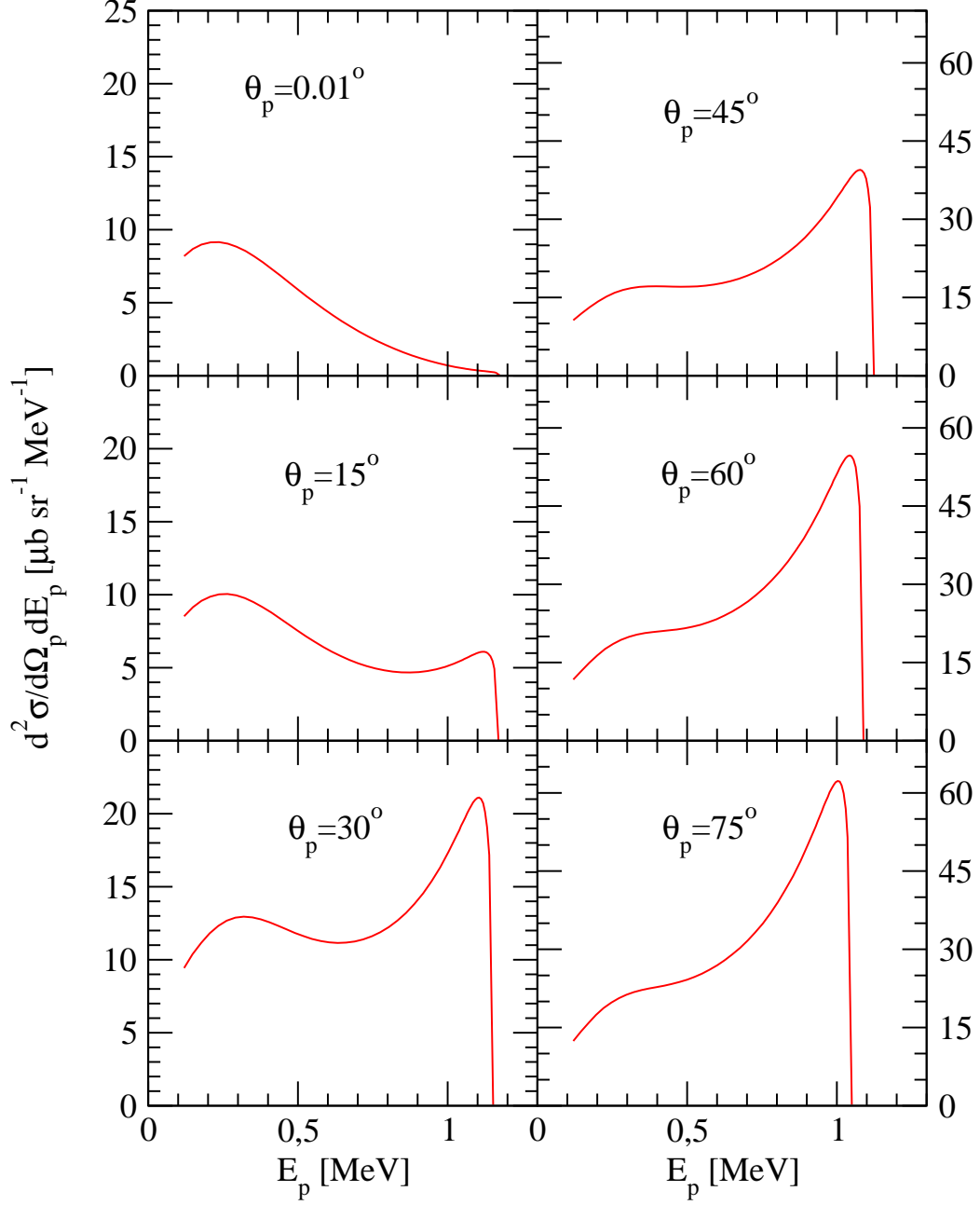


FIG. 10: (color online) The spectra of the outgoing proton from the reaction ${}^3H(\gamma, p)nn$ with $E_\gamma = 10$ MeV at different lab. angles of the proton. They have been calculated using the AV18 [25] NN interaction and the current composed of single nucleon and meson exchange currents [26].

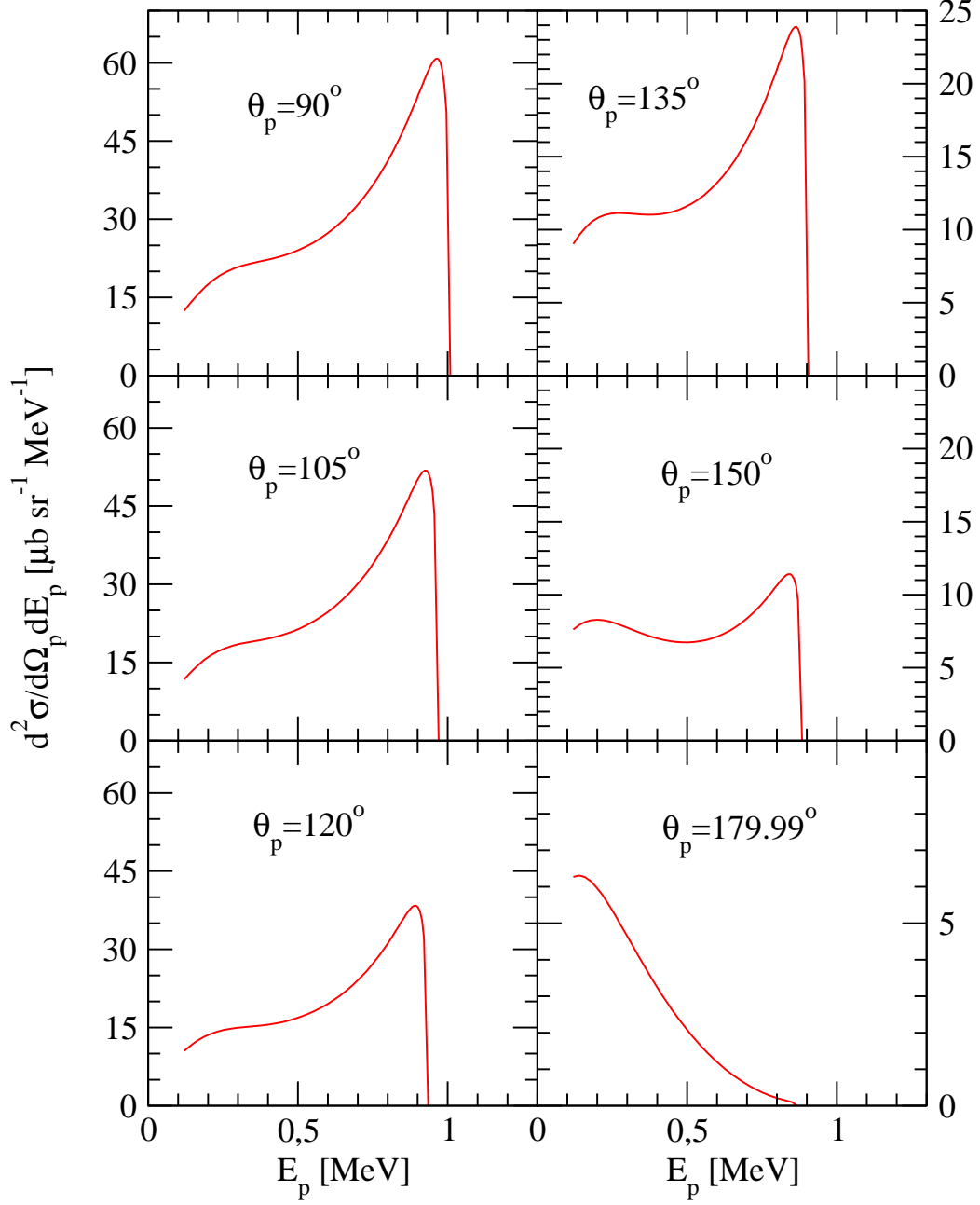


FIG. 11: (color online) The spectra of the outgoing proton from the reaction ${}^3H(\gamma, p)nn$ with $E_\gamma = 10$ MeV at different lab. angles of the proton. They have been calculated using the AV18 [25] NN interaction and the current composed of single nucleon and meson exchange currents [26].